Use of Ocean Stability Data and Machine Learning to Improve Tropical Cyclone Situational Awareness and NHC Statistical-Dynamical Intensity Guidance

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Outline

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- Extended Best Track dataset

Project Motivation

- Dynamical, statistical-dynamical, and consensus models used by NHC for intensity forecasting have all improved considerably since 1990
- From 2017 – 2019 , HWRF outperformed at the shorter forecast lead times (FLTs) ($\leq$ 48 h) two statistical dynamical models:
  - Statistical Hurricane Intensity Prediction Scheme (SHIPS)
  - Logistic Growth Equation Model (LGEM)
- Statistical-dynamical models (SHIPS, LGEM)
  - Are still skillful at all FLTs and better than HWRF at longer FLTs
  - Contribute to improved consensus models
- Recent research suggest that statistical-dynamical models can be further improved by
  - Better representation of TC-ocean interaction and SST cooling
  - Use of non-linear ML methods

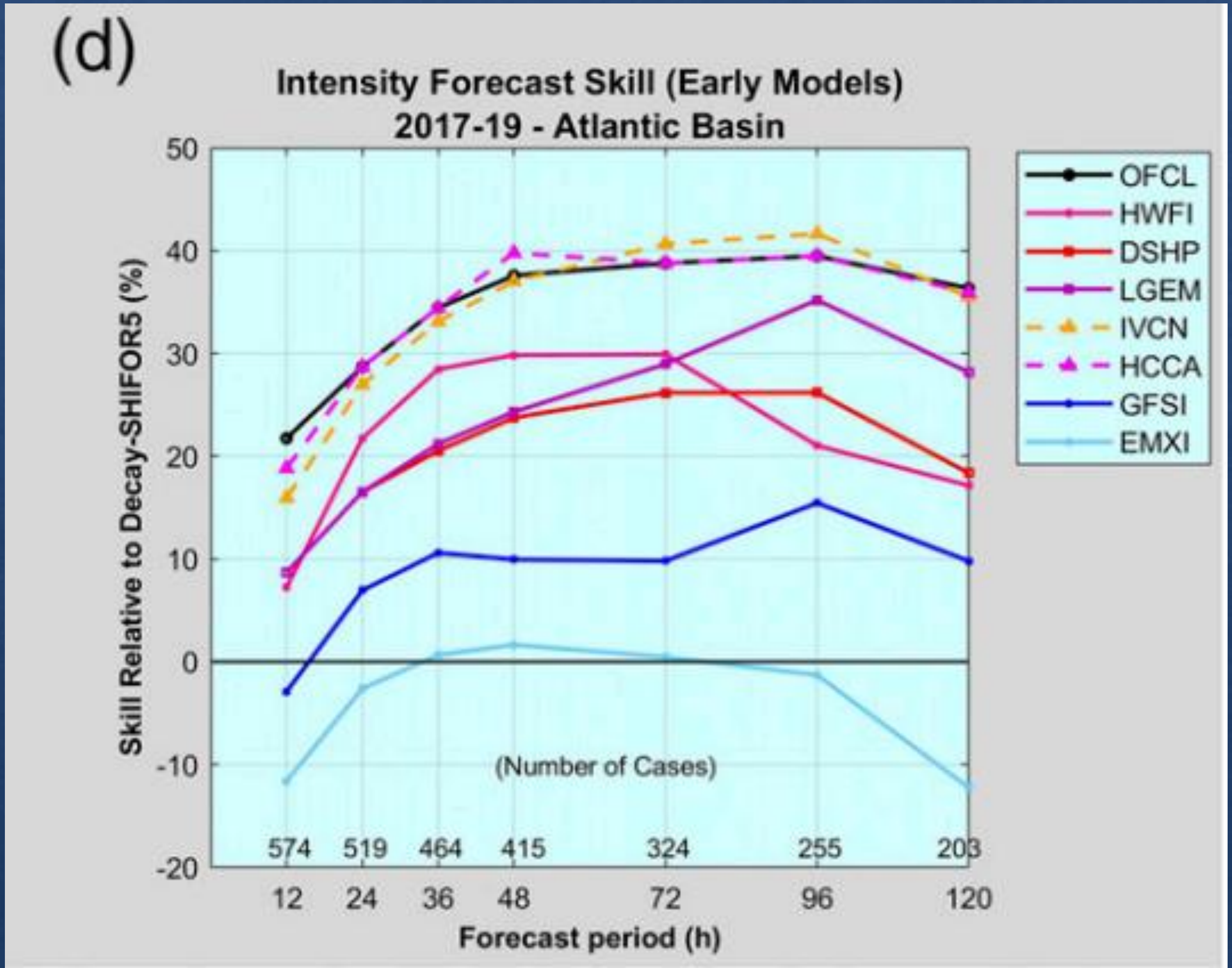


Figure 5d from Cangialosi, et al (2020), Weather and Forecasting

Ocean Heat Content

- Ocean susceptibility to SST cooling is commonly estimated using OHC

$$OHC(x, y) = \rho_0 C_p \int_{Z_{26}}^{0} (T_i\ (x, y, z)\ - 26°\mathrm{C})\ dz$$

where

  - x, y, (z) are horizontal (vertical) coordinates
  - T(x, y, z) is ocean temperature,
  - ρ_0 is seawater density,
  - C_p is heat capacity
  - Z_{26} is the depth of the 26°C isotherm
- OHC is the primary product used by NHC qualitatively to evaluate the ocean susceptibility to SST cooling, and is also a strong predictor in statistical-dynamical models
- OHC, however,
  - provides no information when SST is below 26^{o}C,
  - has limited utility and must be calculated differently in shallow regions where the temperatures at all depths are above 26^{o}C
  - includes only indirect information about ocean static stability

Ocean communicates with TCs through SST, not OHC, and the most important factors that determine the TC-induced SST cooling are the strength of the TC's mixing and the ocean's stratification, which are not always represented in OHC (Balaguru et al. 2018)

Ocean Vertically Averaged Temperature

Vertically averaged ocean temperature

$$T_{\overline{d_{MIX}}}(x, y) = \frac{1}{d_{MIX}} \int_{-d_{MIX}}^{0} (T_i\ (x, y, z))\, dz,$$

where d_{MIX} is the depth of storm-induced ocean mixing

- is a better predictor of the SST experienced by a TC (Price 2009)
- $T_{\overline{d_{MIX}}}$
  - can be estimated using a constant d_{MIX} = 100 m or d_{MIX} = 80 m
  - in reality, d_{MIX} depends on TC intensity and translation speed, as well as the temperature and salinity structure of the upper ocean.
- Balaguru et al. (2015) developed an analytical expression for d_{MIX}

$$L_{MIX} = h_{ml} + SC$$

where h_{ml} is the initial mixed layer depth, and *SC* is the stability correction that accounts for the magnitude of TC-induced deepening of the mixed layer,

$$SC = 2\ (\rho(u^*)^3 t)\ (\kappa g \alpha)^{-1}$$

where ρ is ocean density, u^* is wind friction velocity, t is the time over which the mixing takes place, κ is the von Karman constant, g is the acceleration of gravity, and α is the rate of change of density with depth below the mixed layer.

Ocean Vertically Averaged Temperature

Vertically averaged ocean temperature

$$T_{\overline{d_{MIX}}}(x,y) = \frac{1}{d_{MIX}} \int_{-d_{MIX}}^{0} (T_i\ (x,y,z))\ dz,$$

- where d_{MIX} is the depth of storm-induced ocean mixing

- For a given h_{ml}, L_{MIX} increases with
  - stronger winds
  - slower translation (or larger storm)
  - weaker stratification
- L_{MIX} agrees well with d_{MIX} estimates by more complex numerical ocean models
- The dynamic temperature, T_{dy}, can then be calculated by setting $d_{MIX} = L_{MIX}$, and using a pre-storm temperature profile for T, to estimate the SST that a TC will experience
- T_{dy} is a more general ocean cooling parameter than OHC, since T_{dy} takes into account the upper ocean temperature structure, static stability effects, and the storm's translation speed and intensity

Improved Depth-Averaged Temperature
CMIP6 High-Resolution Model Data (HighResMIP)

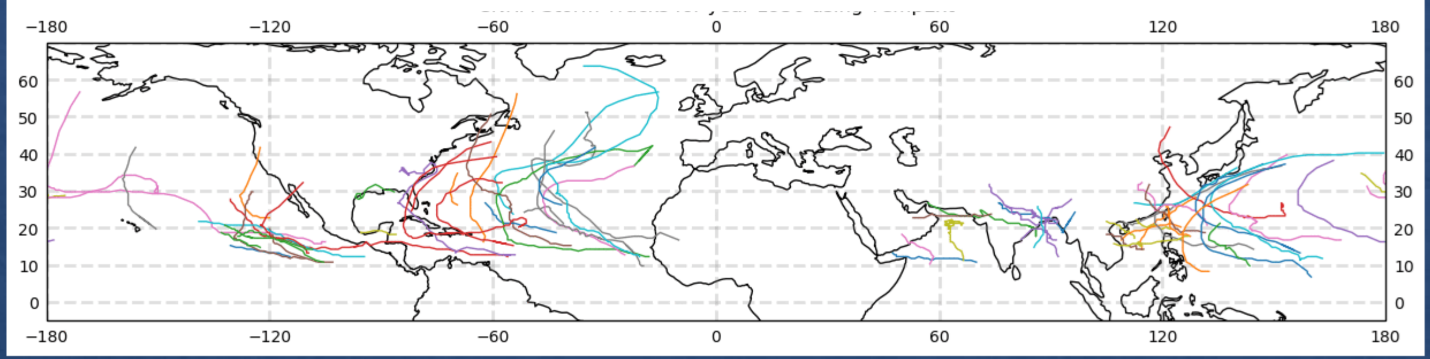
- T_{dy}
  - Is based on a simple 1-d energy balance (mixing, stratification at one location)
  - Does not include effects that depend on the spatial TC structure and TC translational speed (Ekman pumping)

- Coupled Model Intercomparison Project (CMIP6)model output can help us determine whether a correction to T_{dy} might produce better estimates of storm-cooled SSTs
- CMIP6 archive includes 1950 control run simulations from over 20 modelling centers submitted to the High Resolution Model Intercomparison Project (HighResMIP)

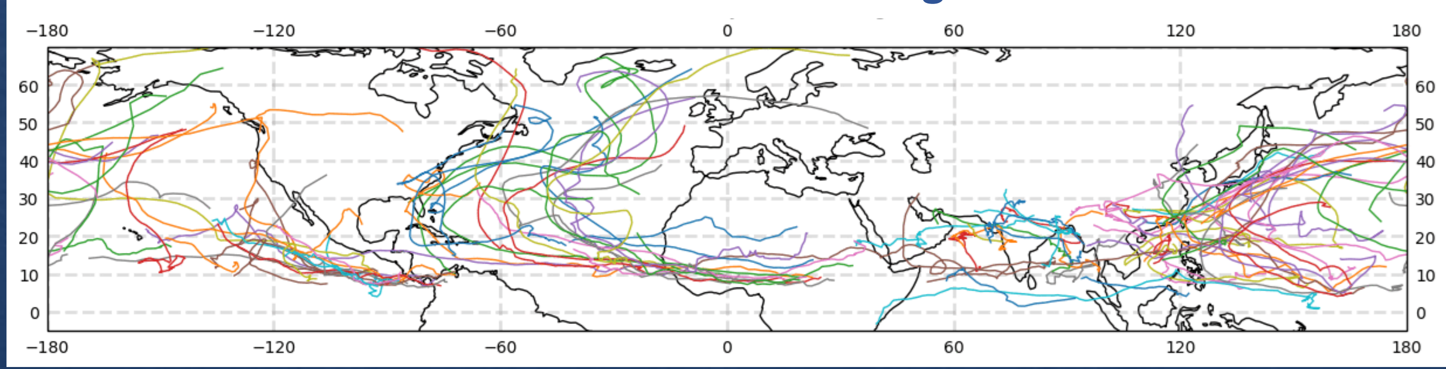
- 3 models produce realistic tropical cyclones of at least category 3
  - Centro Euro-Mediterraneo sui Cambiamenti Climatic (CMCC) CM2-VHR4 Model
    - 0.25^{o} atmosphere, 0.25^{o} ocean resolution
  - Centre National de Recherches Meteorologiques and CERFACS (CNRM) CM6-1-HR Model
    - 0.5^{o} atmosphere, 0.25^{o} ocean resolution
  - European Centre for Medium Range Weather Forecasts (ECMWF) IFS-HR Model
    - 25 km atmosphere and 25 km ocean
- Output/products available from 100-year control simulations:
  - Atmosphere: 6-h temperature profiles, u- and v- components of surface winds, sea-level pressure; daily SST
  - Ocean: daily SST; monthly potential temperature, salinity, mixed-layer depth
  - Storm tracks for TCs

CMIP 6 Simulated Storm Tracks

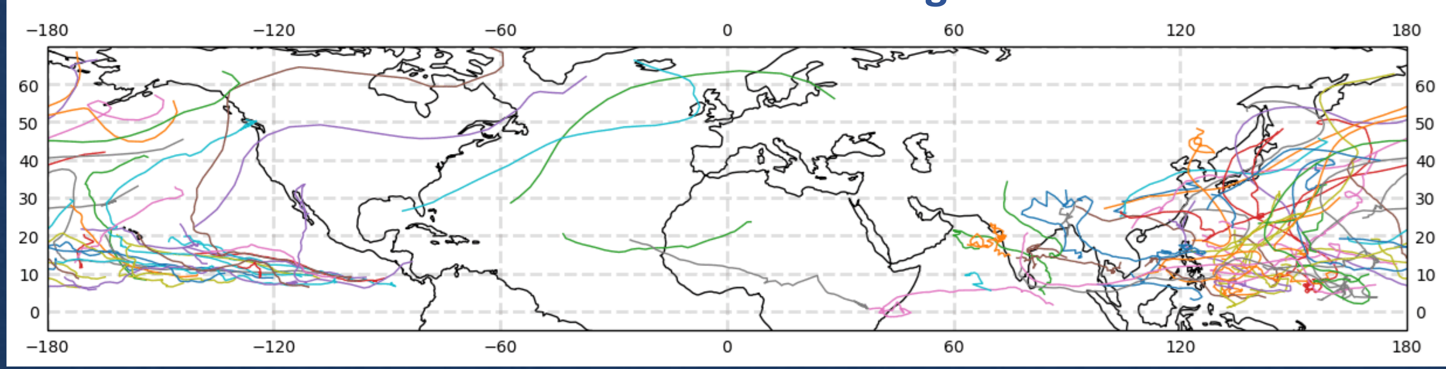
CNRM-CM6-1-HR: TempestExtremes Algorithm



CNRM-CM6-1-HR: TRACK Algorithm



CMCC-CM2-VHR4: TRACK Algorithm



Two algorithms have been developed to track simulated tropical storms: TRACKS and TempestExtremes (TempExt)

Track data is available for two of the models

- TRACKS and TempExt for CNRM-CM6-1-HR
- TRACKS for CMCC-CM2-VHR4

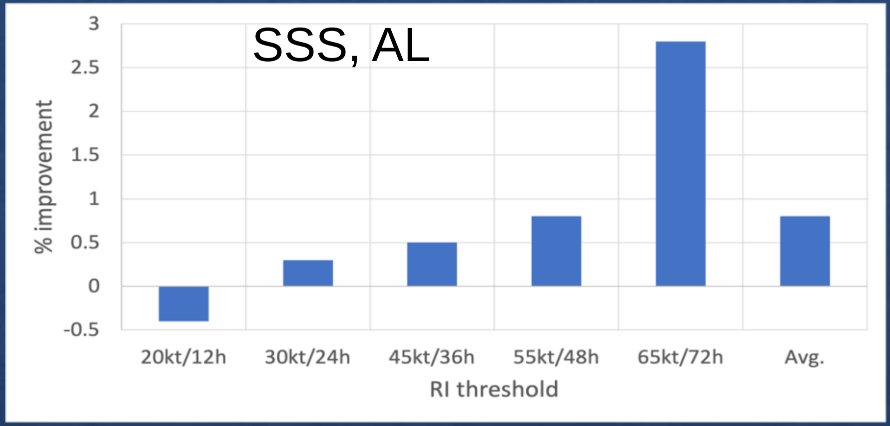
TRACK algorithm generally picks up and tracks more tropical storms

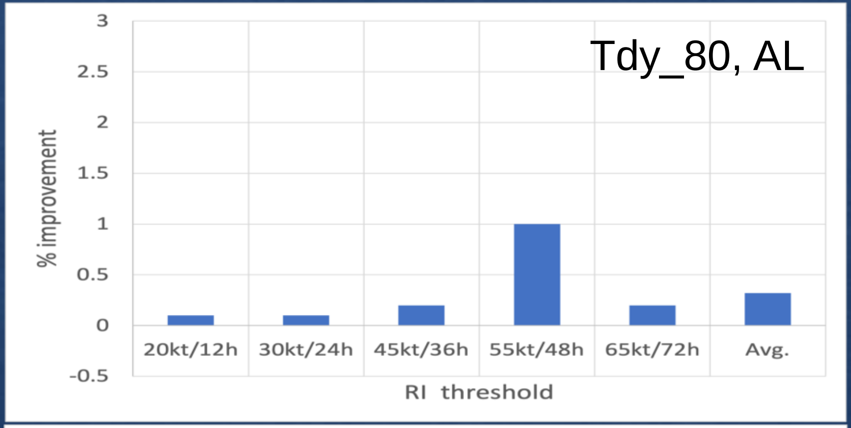
CNRM-CM6-1-HR has good coverage in all basins, whereas CMCC-CM2-VHR4 lacks storms in the Atlantic basin

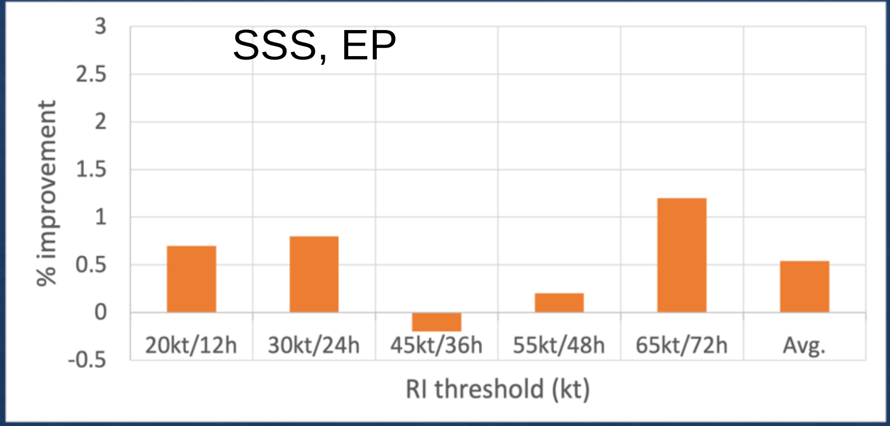
Next Step: calculate daily SST changes before and after storm passage and use these to relate T_{dy} to model fields such as surface wind, surface pressure, and mixed layer depth

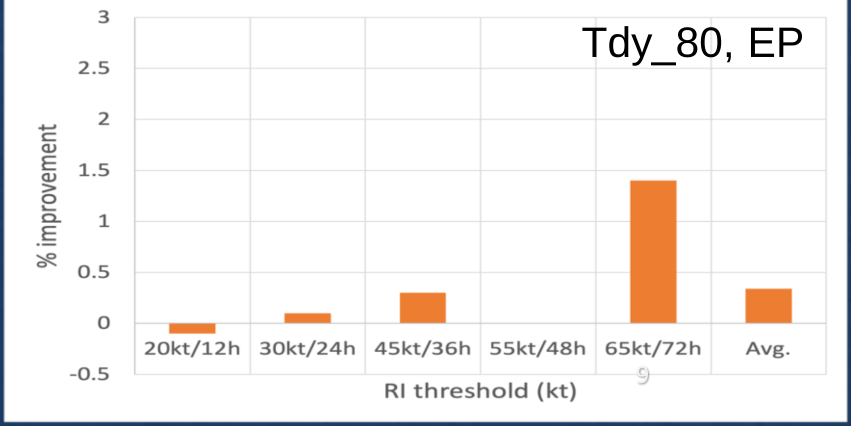
RII with SSS and Tdy

- Sea-Surface Salinity (SSS) and Dynamic Temperature (Tdy) were tested as additional SHIPS-RII predictors
- SSS predictor was determined from NCODA climatological salinity data (EP) and full salinity data (AL)
- Tdy predictor used was difference between Tdy (computed assuming constant mixing depth of 80 m) and SST determined from NCODA analyses
- SSS and Tdy predictors were added to operational 2021 SHIPS-RII and skill differences between enhanced SSS and Tdy versions and operational SHIPS-RII were evaluated
- Sensitivity tests were performed for a homogenous sample of cases from the developmental SHIPS 2007-2020 database
- Skill Improvement of 0.5% or more is considered significant, especially from adding a single predictor









Different versions of SST cooling

- Empirical J Cione cooling currently used in SHIPS, LGEM, SHIPS-RII (for the Atlantic Basin Only)
  - SST_cool_200km = 1.1222793*SST + 0.1425625*c - 0.0778590*rlat - 3.3705640
    - SST_cool_200km = cooled SST within 200 or 60 km of storm center) in deg C
    - SST = pre-storm SST in deg C
    - c = storm translational speed in m/s
    - rlat = storm center latitude in deg N
- Testing several empirical versions of SST cooling derived by Joe Cione, Joshua Wadler, and John Knaff
- Working on comparing empirical SST cooling with Tdy
  - Empirical equations for SST_cool as a function of various ocean and storm parameters, including SST, OHC, D26, Lat, Vmax, MSLP, c_tr, and storm size
  - Multiple versions of Tdy = f(Vmax, c_tr, storm size)
    - Basin-wide display on SLIDER, AWIPS2
      - Using constant mixing depth = 80m, 100m
      - Using basin-averaged values for Vmax, c_tr, storm size
      - Using c_tr estimated from 850 – 400 hPa GFS horizontal wind
    - As predictors for SHIPS, LGEM, RII
      - Tdy using Vmax, c_tr, storm size at t = 0
      - Fully dynamical Tdy
- Adding MPI, SST cooling, Tdy to experimental SHIPS lsidag files

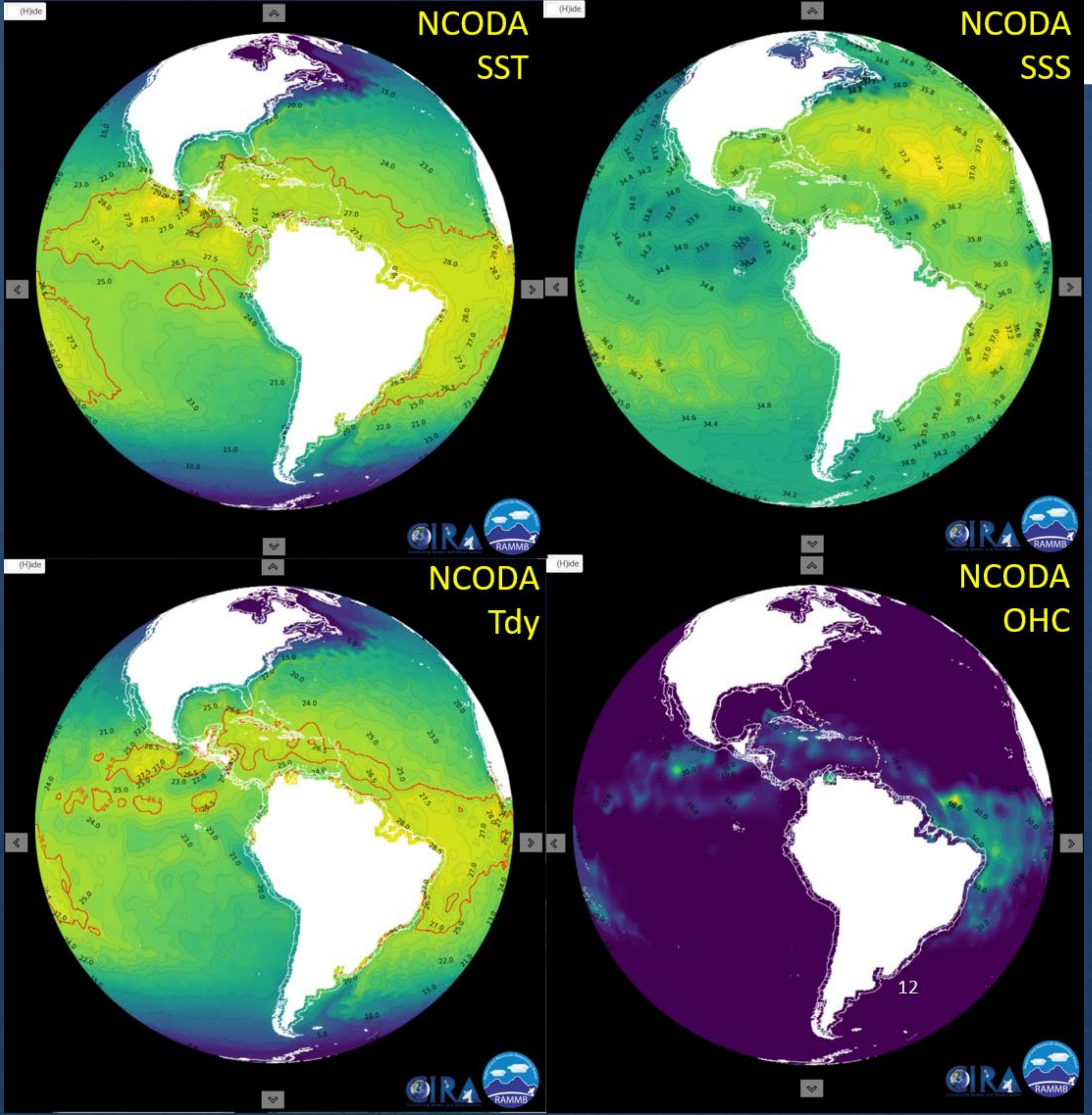
Real-Time NCODA SST, SSS, OHC, and Tdy on SLIDER

- All four products, SST, SSS, OHC, and dynamic depth-averaged temperature (Tdy) are available in near-real time on SLIDER https://rammb-slider.cira.colostate.edu/

- All 4 NCODA products are global

- Running in near-real-time for GOES-16 area.
  - Working on implementing for GOES_17, Himawari
  - Considering implementing for Met6eosat-8, -11
  - Running for all 5 satellite will provide global coverage on SLIDER

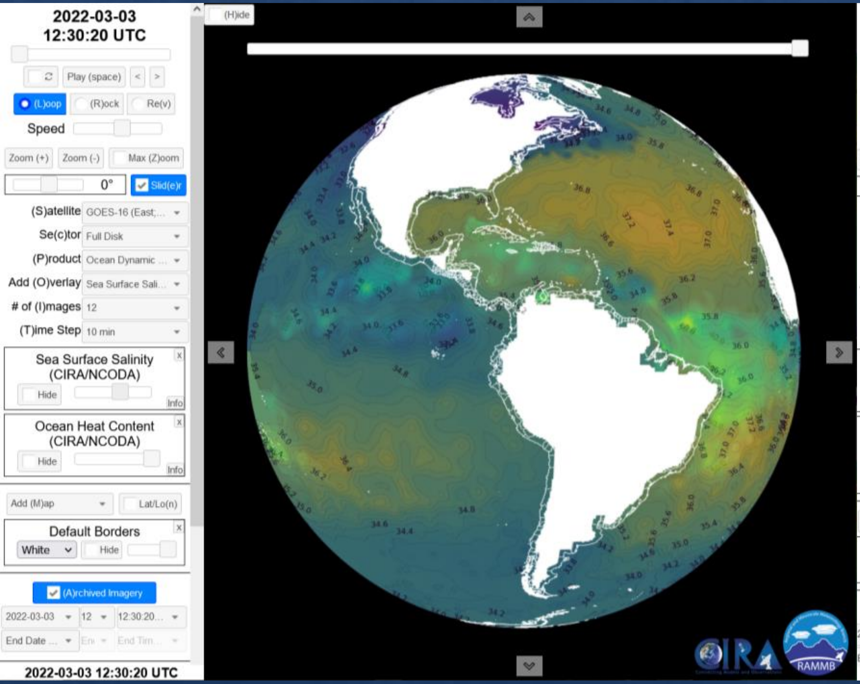
- Working on improved color scale and using better approximations for Vmax, c_tr, and storm size to estimate Tdy



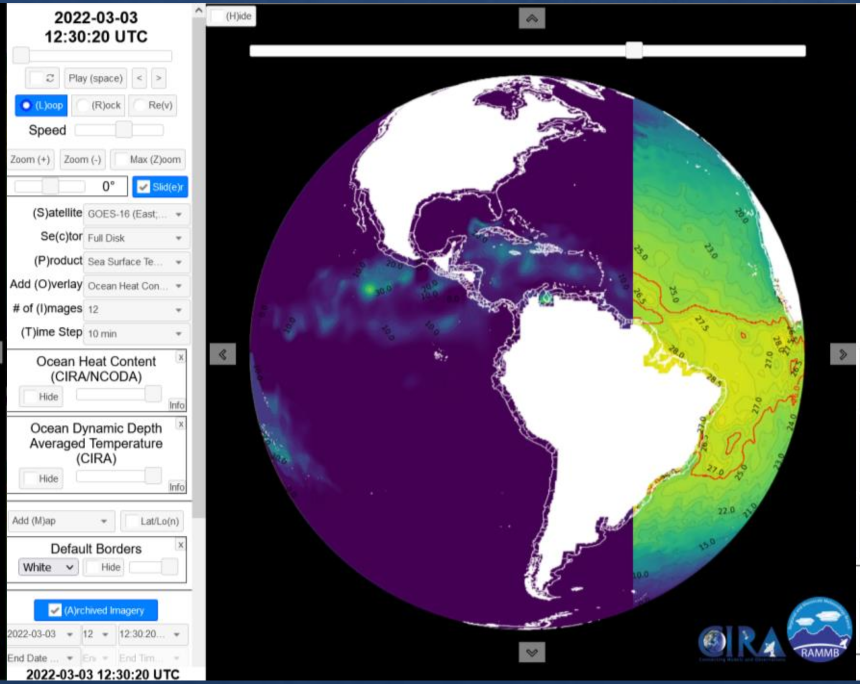
Real-Time NCODA SST, SSS, OHC, and Tdy on SLIDER

- RAMMB-CIRA SLIDER https://rammb-slider.cira.colostate.edu/ allows users to overlay or compare different products
- All four NCODA products, SST, SSS, OHC, and dynamic depth-averaged temperature (Tdy) are available on SLIDER in near real-time
- Can use SLIDER feature to directly compare and overlay NCODA products, and combine NCODA products with satellite imagery

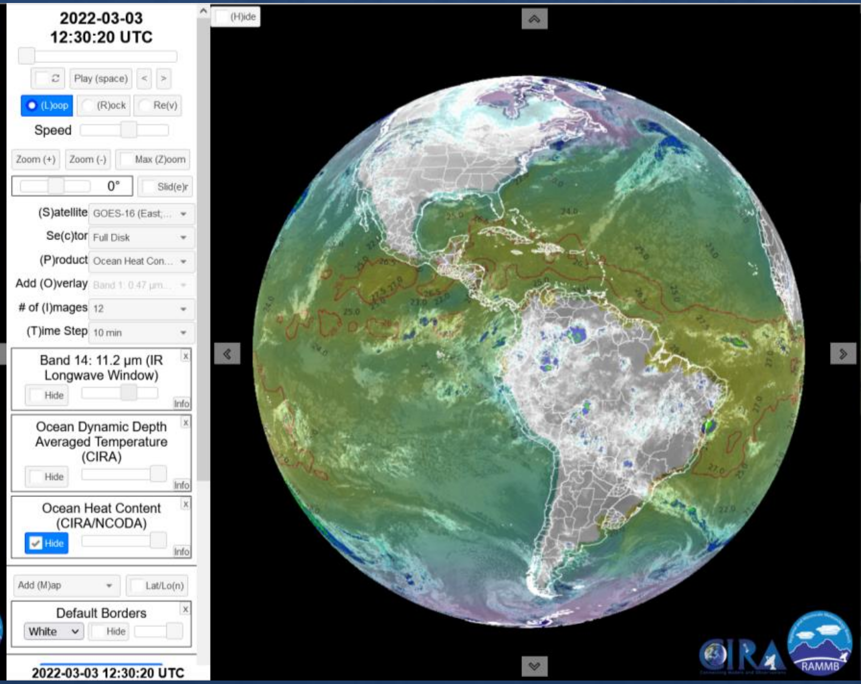
SSS on top of OHC



OHC (left) and Tdy (right)



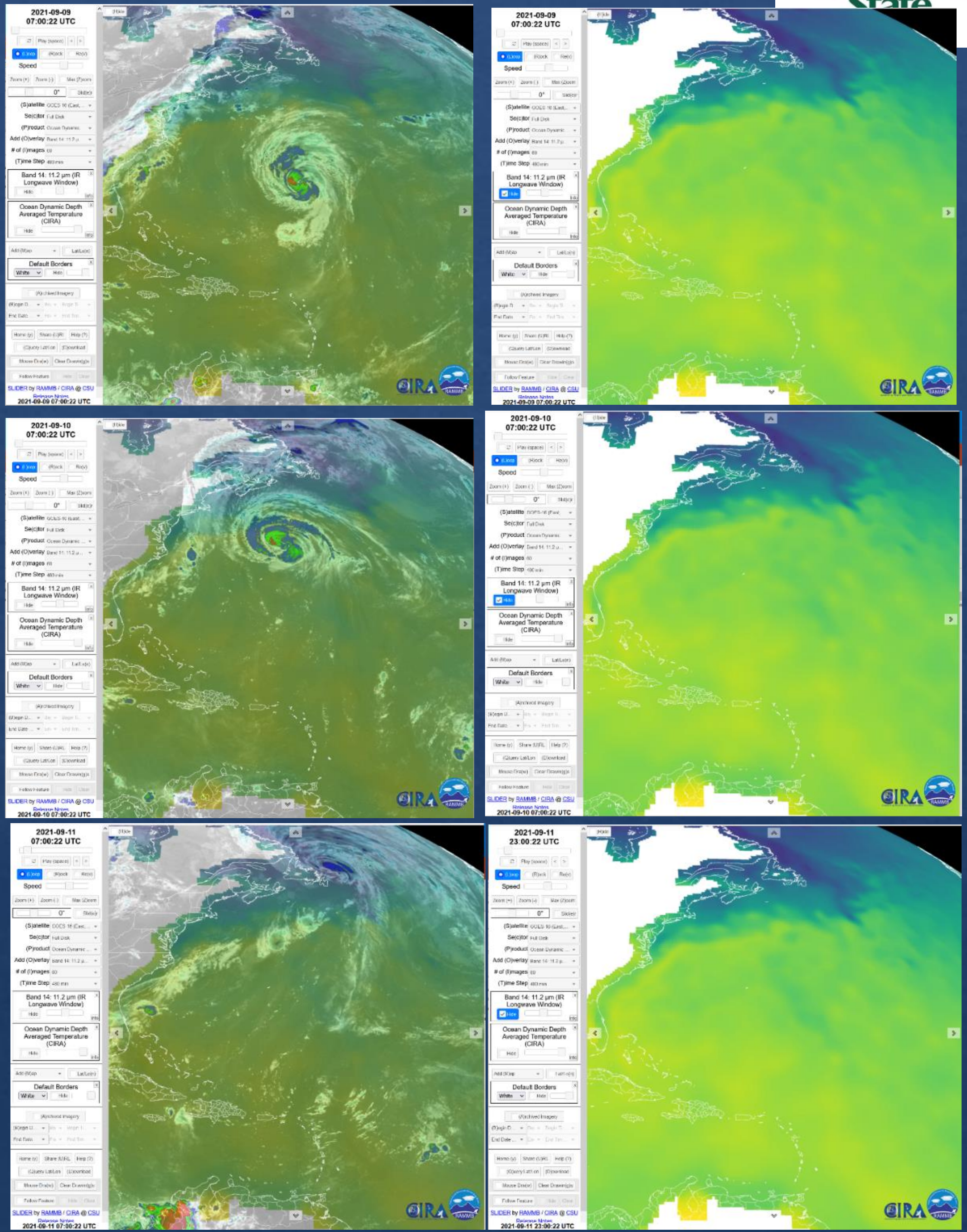
GOES-16 band 14 (11.2 µm on top of Tdy



NCODA Tdy on SLIDER Example

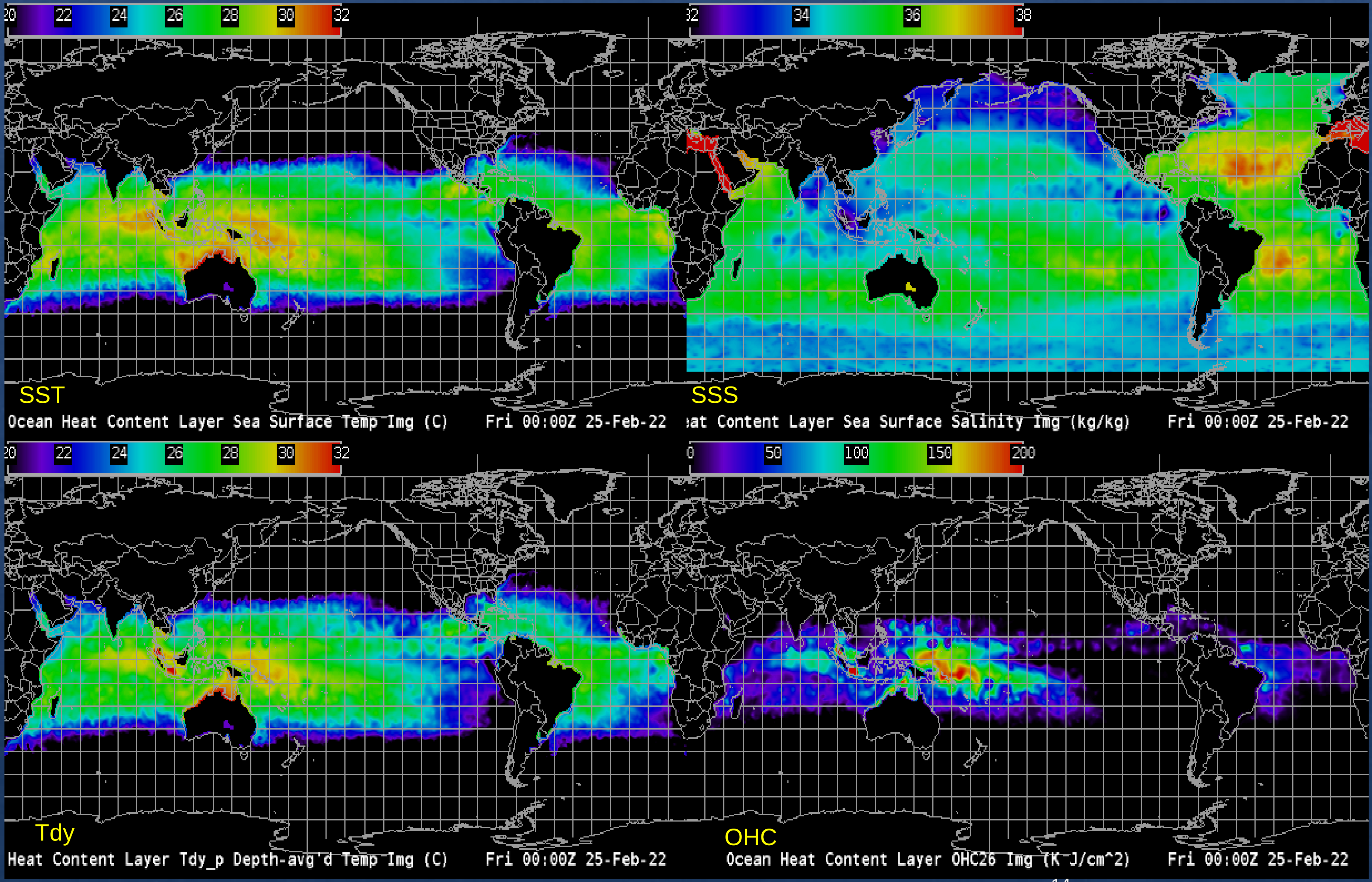
- NCODA-based dynamic depth-averaged temperature is available on SLIDER, https://rammb-slider.cira.colostate.edu/

- Example of using SLIDER to combine Tdy and GOES satellite imagery:
  - T_{dy} and GOES-16 IR LW Channel 14 (11.2 μm) on top of T_{dy} (right)
  - and T_{dy} (right).
  - On the images for 09/10 (middle row) and 09/11 (lower row) the cold wake of Hurricane Larry is clearly visible.



Real-Time SST, SSS, OHC, and Tdy in AWIPS2

- AWIPS2 display of NCODA SST, SSS, OHC, and Tdy has been developed ahead of schedule
- All 4 products are running at CIRA AWIPS2 in real-time
- Begun coordinating with JHT on setting up AWIPS2 demonstration for NHC forecasters
- Working on making AWIPS2 display of NCODA variables available to JTWC
- Will coordinate with TOWER-S group on the possibility of using cloud AWIPS2 for demonstrations



Work in Progress

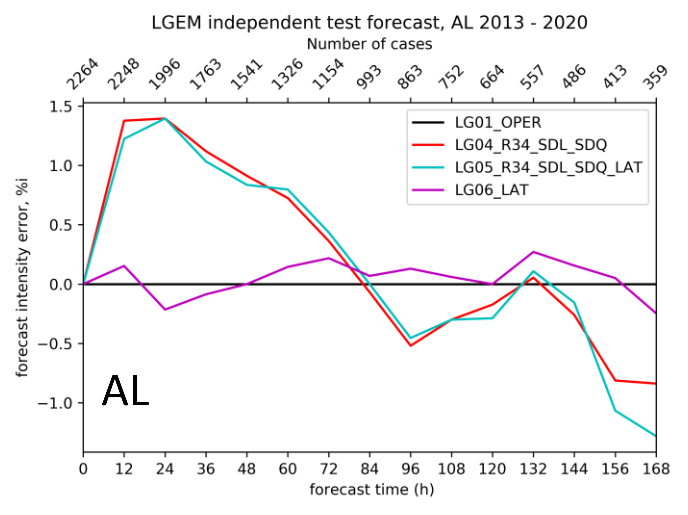
- Implement fully dynamic version of Tdy
- Test in SHIPS, LGEM, RII
- Evaluate the use of different SST cooling parameterizations vs Tdy
- In the updated model with Tdy replace regression with a nonlinear ML method

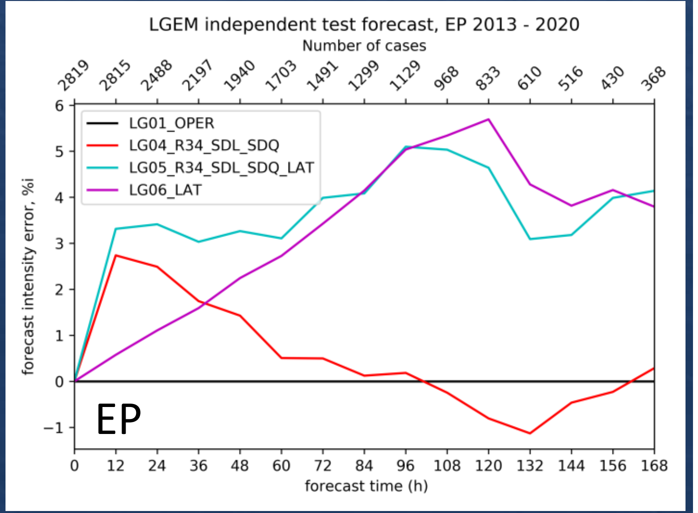
- Demonstrate in real-time SST, SSS, Tdy, OHC to NHC and JTWC forecasters via AWIPS2 and SLIDER (Summer 2022)
- Demonstrate updated SHIPS, LGEM, RII (Summer 2023)

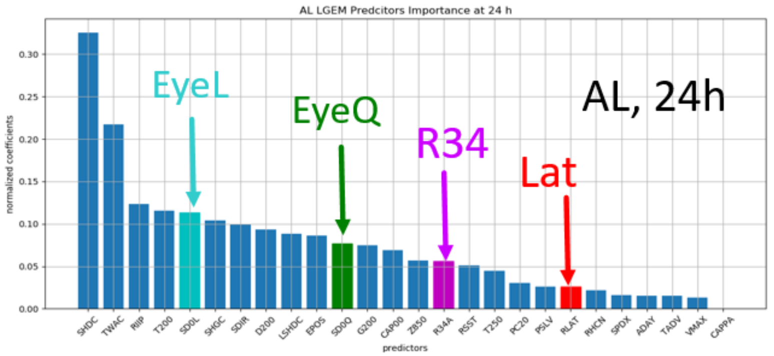
SHIPS, LGEM, RII with storm structure predictors (JHT)

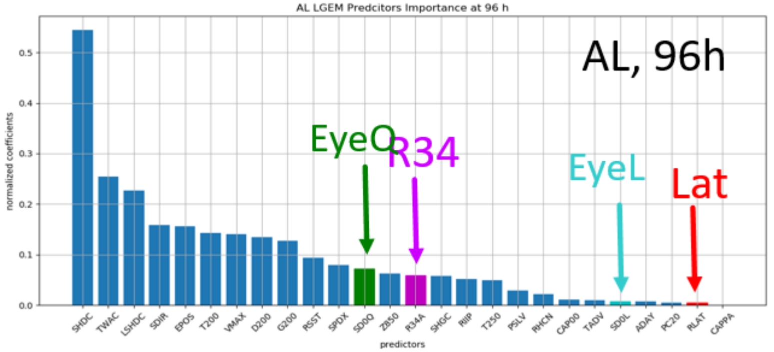
- SHIPS, LGEM: adding four new predictors
  - non-zero averaged radius of 34 kt winds (R34A)
  - probability of the eye existence at t = 0 based on
    - Linear discriminant Analysis (EyeL)
    - Quadratic Discriminant Analysis (EyeQ)
  - time-averaged latitude (RLAT)

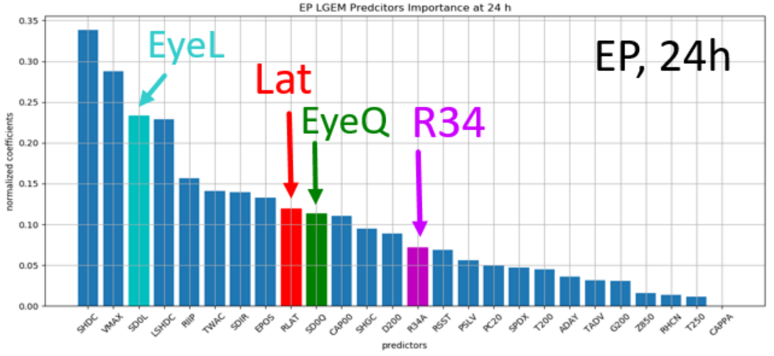
  produces overall the best improvement for both SHIPS and LGEM for the Atlantic and east Pacific for most forecast lead times.
- SHIPS-RII, the addition of RMW, R34A, and eye-existence probability predictors was found to provide the most improvement in forecast skill
- SHIPS, LGEM: error reduction of 1.2 – 3.2 % at forecast lead time of 12 h, and up to 5 % at later forecast times
- Most improvement for LGEM for the east Pacific
- Improvements are significant compared to the historical improvements in SHIPS and LGEM
- The most notable is the improvement for the short forecast lead times (6 – 24 h) for which historically forecast errors have improved slower than for longer forecast lead times

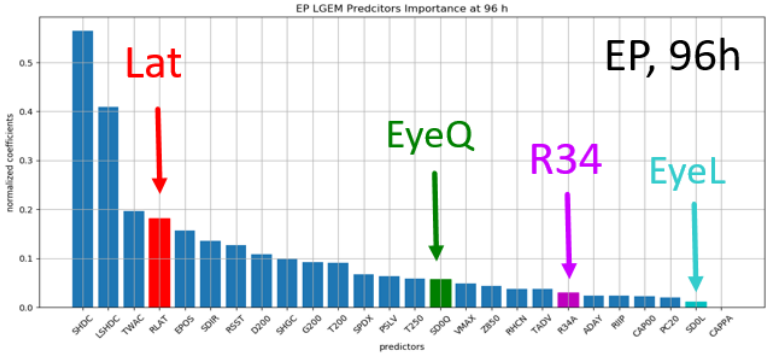












Extended Best Track Dataset (EBTRK)

AL312020	IOTA	111406	2020	13.3	75.0	35	1004	70	-99	1011	270	80	80	0	0	0	0	0	0	0	0	0	0	*	256	0900
AL312020	IOTA	111412	2020	12.9	75.7	40	1002	55	-99	1011	270	80	80	0	0	0	0	0	0	0	0	0	0	*	235	0900
AL312020	IOTA	111418	2020	12.5	76.4	45	997	40	-99	1011	270	80	80	0	0	0	0	0	0	0	0	0	0	*	233	0900
AL312020	IOTA	111500	2020	12.6	76.7	55	992	35	-99	1011	270	90	80	30	70	40	40	0	0	0	0	0	0	*	260	0900
AL312020	IOTA	111506	2020	13.0	77.1	65	988	20	-99	1011	270	100	80	40	90	40	40	20	30	20	0	0	20	*	322	0900
AL312020	IOTA	111512	2020	13.1	78.0	70	982	20	-99	1011	270	120	90	50	100	50	40	30	50	20	20	0	20	*	396	0900
AL312020	IOTA	111518	2020	13.2	78.9	75	974	20	-99	1011	270	140	100	70	120	60	50	40	60	25	20	0	20	*	418	0900
AL312020	IOTA	111600	2020	13.2	79.8	90	961	15	-99	1011	270	160	120	80	140	70	60	40	70	30	25	20	25	*	391	0900
AL312020	IOTA	111606	2020	13.4	80.7	120	935	10	15	1011	270	180	130	90	160	80	60	40	80	35	30	25	35	*	291	0200
AL312020	IOTA	111612	2020	13.5	81.5	135	917	10	10	1011	270	200	130	100	180	80	60	50	80	40	30	25	40	*	205	0200
AL312020	IOTA	111618	2020	13.5	82.3	130	918	10	10	1011	270	200	130	100	180	80	60	50	80	40	30	25	40	*	127	0200
AL312020	IOTA	111700	2020	13.6	83.0	130	918	15	-99	1011	270	200	130	100	180	80	60	50	80	40	30	25	40	*	62	0900
AL312020	IOTA	111706	2020	13.7	83.8	110	935	20	-99	1011	270	190	130	80	180	70	60	30	60	35	25	15	25	*	-22	0900
AL312020	IOTA	111712	2020	13.7	84.7	75	965	25	-99	1010	250	170	110	50	160	60	40	0	50	30	0	0	20	*	-119	0900
AL312020	IOTA	111718	2020	13.7	85.7	55	988	55	-99	1010	230	150	70	0	140	60	0	0	0	0	0	0	0	*	-225	0900
AL312020	IOTA	111800	2020	13.8	86.7	40	1000	120	-99	1010	210	140	0	0	130	0	0	0	0	0	0	0	0	*	-162	0900
AL312020	IOTA	111806	2020	13.8	87.8	35	1005	140	-99	1010	210	140	0	0	0	0	0	0	0	0	0	0	0	*	-91	0900
AL312020	IOTA	111812	2020	13.7	89.0	25	1006	140	-99	1010	210	0	0	0	0	0	0	0	0	0	0	0	0	*	-71	0900

- Available online for the Atlantic (1851 – 2020), east Pacific (1949 – 2020), central Pacific (1950-2020)
  https://rammb2.cira.colostate.edu/research/tropical-cyclones/tc_extended_best_track_dataset/
  - Internal CIRA version for West Pacific, Indian Ocean, Southern Hemisphere
- The EBTRK makes the historical ATCF data more accessible
  - can be easily imported to Python Pandas dataframe or Excel
  - includes variables not available in other common ATCF databases such as HURDAT2
  - Some variables are calculated from both b-deck and a-deck
- Provides Vmax, MSLP, wind radii, RMW, Router, Pouter, Eye Diameter, Distance To Land
- Originally developed by M. DeMaria and J. Knaff was completely revisited, including developing the new Python code, cleaning up the dataset to match the most up-to-date NHC and JTWC data, fixing errors, extending for all 6 basins to use all available historical ATCF data, and designing a new format that can be used for all 6 basins.
- Plan to updated for 2021 when final Best Track data for 2021 become available, and also update for recent changes in NHCs b-deck data for 1966 - 1970